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Search for Flavor-Changing Neutral Current Decays of the Top Quark in p$\overline{\text{p}}$ Collisions at $\sqrt{s}$ = 1.8 TeV

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We search for the flavor-changing neutral current decays of the top quark $t \rightarrow q\gamma$ and $t \rightarrow qZ$ (here q represents the c and u quarks) in $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. We use a dataset ($\int \mathcal{L}dt \sim 110\text{pb}^{-1}$) collected during the 1992-1995 run of the Collider Detector at Fermilab. We set 95% confidence level limits on the branching fractions $B(t \rightarrow q\gamma) < 3.2\%$ and $B(t \rightarrow qZ) < 33\%$, consistent with the Standard Model.

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Physics beyond the Standard Model can manifest itself by altering the expected rates of flavor-changing neutral current (FCNC) interactions. As an analogous historical example within the Standard Model, the presence of the charm quark can be inferred from its effect on the branching fraction $B(K_L^0 \rightarrow \mu^+\mu^-)$ [1]. FCNC decays of the top quark are of particular interest [2,3]. The large mass of the top quark suggests a strong connection with the electroweak symmetry breaking sector. Evidence for unusual decays of the top quark might provide insights into the mechanism of electroweak symmetry breaking. For the top quark, the FCNC decays $t \rightarrow qZ$ and $t \rightarrow q\gamma$ (where q denotes either a c- or a u-flavored) are expected to be exceedingly rare [4] and any observation of these decays in the presently available data would indicate new physics.

We present results using data from proton-antiproton collisions at a center of mass energy of 1.8 TeV collected at the Collider Detector at Fermilab (CDF) during the 1992-1995 run of the Fermilab Tevatron ($\int \mathcal{L}dt \sim 110\text{pb}^{-1}$). The CDF detector is described in detail elsewhere [5]; a brief discussion follows.

In the CDF detector, a 51 cm long silicon vertex detector (SVX) [8], located immediately outside the beampipe, provides precise track reconstruction in the plane transverse to the beam, and is used to identify secondary vertices that can be produced by b and c quark decays. Because $p\overline{p}$ interactions are spread along the beamline with a standard deviation of about 30 cm, slightly more than half of the events originate from primary vertices inside the SVX fiducial region. The momentum of charged particles is measured in the central tracking chamber (CTC), which sits inside a 1.4 T superconducting solenoidal magnet. Outside the CTC are electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, covering the pseudorapidity region $|\eta| < 4.2$. [6] In the central ($|\eta| < 1.0$) electromagnetic calorimeter, finely segmented proportional chambers (CES) used to measure transverse shower profiles are placed at a depth of approximately 6 radiation lengths. Jet, photon and electron candidates are identified in the calorimeters, as is the missing transverse energy $\not\!\!E_{\rm T}$ [7]. Surrounding the calorimeters, drift chambers in the region $|\eta| < 1.0$ provide muon identification. A three level trigger selects events with high transverse momentum electrons, muons and/or photons for this analysis.

At CDF, a photon is identified as an energy cluster in the electromagnetic calorimeter with no track pointing at it. To improve identification efficiency, we additionally permit one single soft track (presumably from a random overlap) with less than 10% of the energy of the photon to point at the cluster. For the typical photon shower, the electromagnetic cluster consists of two adjacent calorimeter towers. The energy of the photon is measured in the calorimeter, and the direction of the photon is defined by a line between the event vertex and the centroid of the EM shower as measured in the CES. To reduce backgrounds from hadronic jets, we require that the energy in a cone of $\Delta R = 0.4$ (where $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$) around and excluding the photon candidate be less than 15% of the photon energy. To reduce the background from neutral hadrons, the ratio of energy deposited in the hadronic calorimeter to that in the electromagnetic calorimeter is required to be less than $0.055 + 0.00045 \times E$, where E is the total energy of the candidate in GeV. To suppress π^0 and multiphoton backgrounds, the transverse shower profile in the CES and the energy sharing between the calorimeter towers must be consistent with a single electromagnetic shower.

An electron is also identified as an energy cluster in the electromagnetic calorimeter, this time with a single track pointing to it. The energy of the cluster and the momentum of the track are required to be equal within measurement uncertainties, and the extrapolation of the track to the CES is required to match the measured position of the shower in the CES. Only electrons in the central region ($|\eta| < 1.0$) are used in this analysis.

A muon is identified by requiring a match between the extrapolated track as reconstructed in the CTC and track segments reconstructed in the muon chambers, taking into account multiple scattering of the muon. Furthermore, the energy deposition in the calorimeter must be consistent with a minimum ionizing particle. In this analysis, we restrict ourselves to muons in the central region ($|\eta| < 1.0$). Further details of the electron and muon identification requirements can be found in [9].

A jet is identified by energy deposited in the calorimeters in a cone of $R < 0.4$. Details of the CDF jet reconstruction algorithm can be found in [10].

If the branching fraction of a particle into a particular final state (e.g. a FCNC decay) is x, the branching fraction into another final state (e.g. the decay $t \to Wb$ [11]) can be no larger than $(1-x)$. Therefore, the ratio r of the number of events detected in a rare decay mode normalized to a common decay mode is at least $x/(1-x)$, after corrections for efficiency and acceptance. Measuring r allows us to calculate an upper limit on the branching fraction $x \leq r/(1+r)$, after corrections for misidentification, efficiency and acceptance, and for the fact that in $t\bar{t}$ events there are two top quarks that can decay into a particular final state.

In both the $t \to q\gamma$ and $t \to qZ$ searches, we calculate limits on branching fractions by comparing the number of candidate events in the FCNC candidate samples to the number of $t\bar{t}$ events observed in the normalization sample. Our normalization sample consists of events consistent with the hypothesis where both top quarks decayed via $t \to Wb$ decays, and one W decayed leptonically and the other W decayed hadronically. These events are identified by a high p_T ($p_T > 20$ GeV/c) electron or muon, at least 20 GeV of missing transverse energy from the undetected neutrino, and three or more jets above 15 GeV, at least one of which must be identified as containing a b hadron from the presence of a secondary vertex. [9] This procedure is called "b-tagging" the jet. In a sample of 110 pb^{-1}, we observe 34 $t\bar{t}$ candidates over an estimated background of 9 ± 1.5 events.

At Tevatron energies, the dominant source of top quarks is $t\bar{t}$ pair production from $q\bar{q}$ annihilation. In the search for the decay $t \to q\gamma$ we assume that the other top quark in the pair decays via the decay $t \to Wb$. We consider two event signatures, depending on whether the W decayed leptonically or hadronically. If the W decayed leptonically, we search for events with an identified W (via a lepton with $p_T > 20$ GeV/c and 20 GeV of missing transverse energy carried by the neutrino), a moderately high E_T photon ($E_T > 20$ GeV), and at least 2 jets with $E_T > 15$ GeV. If the W decayed hadronically, we search for events with at least 4 jets (two from the W decay), and a high E_T ($E_T \geq 50$ GeV) photon. One jet must contain a secondary vertex, identifying it as containing a b hadron. The higher E_T requirement on the photon is to reduce the background; events with jets are more common than events with high p_T leptons. In both cases, there must be a photon and jet combination with mass between 140-210 GeV/c^2, consistent with the mass of the top quark. In the non-leptonic case, the remaining jets must have $\Sigma E_T \geq 140$ GeV, consistent with the decay of a second top quark in the event. The b-tagged jet must be associated with the second top combination. 40% of our $t \to q\gamma$ acceptance is in our photon plus multijet mode, and 60% is in the lepton plus photon mode.

Because we are interested in the relative number of events with Standard Model and FCNC signatures, we calculate the ratio of acceptances and efficiencies in the two decay modes. To do this, we use the ISAJET [12] Monte Carlo event generator and a parametric simulation of the CDF detector. Results are shown (relative to the Standard Model $WbWb$ signature, and including branching fractions) in Table I. The first uncertainty is the uncertainty in the relative acceptance; the second is the effect of the b-tagging efficiency of (45 ± 5)% per b jet contained in the SVX fiducial region. Positive (negative) uncertainties indicate that the change in relative efficiency is in the same (opposite) direction as the change in b-tagging efficiency. In 110 pb^{-1} of data, one event is observed in the leptonic channel and no events are seen in the non-leptonic (*i.e.* photon plus multijet) channel. We expect a background of less than half an event in each channel. To set a conservative limit, we assume any events passing the cuts are signal and do not subtract this background.

The single event that passes all selection requirements has a 72 GeV muon, an 88 GeV photon, 3 jets, and a missing transverse energy of 24 GeV. While it enters the FCNC decay candidate sample, this event is also kinematically consistent with the decay $t \to W^+b$, $\bar{t} \to W^-\bar{b}\gamma$, followed by $W^+ \to \mu^+\nu$ and $W^- \to$ jets. However, the photon E_T is exceptionally large for this decay.

Observation of one event passing the selection requirements implies a 95% confidence limit of fewer than 6.45 events (including systematic uncertainties) which translates into a branching fraction limit of

$$B(t \to c + \gamma) + B(t \to u + \gamma) < 3.2\%.$$

The statistical uncertainty in the number of events in the normalization sample is the dominant source of systematic uncertainty. The uncertainty in b quark identification efficiency also contributes to the overall systematic uncertainty. The uncertainties on acceptance and photon identification are negligible by comparison.

We also search for $t \to qZ$ events, using the channel where the Z decays to e^+e^- or $\mu^+\mu^-$, and the other t quark decays to 3 jets. The expected signature is therefore an event with four jets and with two leptons with an invariant mass consistent with a Z boson. Because the Z branching fraction to charged leptons is small, this analysis is less sensitive than the $t \to q\gamma$ search. Candidate $Z \to l^+l^-$ events were selected from inclusive samples of events with electron and muon candidates selected by the trigger ($\int \mathcal{L}dt = 108$ pb^{-1}) using criteria described in detail in [13]. Z bosons are identified as opposite-charge same-flavor lepton pairs inside the range $75 < M_{l^+l^-} < 105$ GeV/c^2. We require each of the 4 jets to have $E_T > 20$ GeV and be contained in the region $|\eta| < 2.4$.

As before, we use the ISAJET [12] Monte Carlo event generator and a parametric simulation of the CDF detector to calculate the efficiencies and acceptances for top quark pairs to be identified as either Standard Model decay candidates or FCNC decay candidates. Again, we determine the acceptances and efficiencies relative to the Standard Model signal (Table II). The first uncertainty is the uncertainty in the relative acceptance; the second is the effect of the b-tagging efficiency. W and Z branching fractions are included as part of the efficiencies.

There are two comparable sources of background to the $t \to qZ$ signal. One is ordinary Z+multijet production; 0.5 background Z+4 jet events are expected. The second source of background is from Standard Model $t\bar{t}$ events where both W bosons decay leptonically, and the two leptons have an invariant mass that falls within the Z candidate range (0.6 events). A smaller source is diboson (WZ or ZZ) + 2 or more jet events in which the Z decays leptonically (0.1 events). The total background is approximately 1.2 events. As before, to set a conservative limit, we assume any events passing the selection requirements are signal and do not subtract this background.

A single $Z \to \mu^+\mu^-$ event passes all the selection requirements. The event kinematics better fit the Z+multijet hypothesis than the FCNC decay hypothesis, particularly the low transverse energies of two of the jets.

Observation of one event passing the selection requirements implies a 95% confidence limit of fewer than 6.4 events (including systematic uncertainties), which translates to a branching fraction limit

$$B(t \to c + Z) + B(t \to u + Z) < 33\%.$$

As before, the systematic uncertainties are dominated by the statistical uncertainty in the number of events in the normalization sample, followed by the uncertainty in b tagging efficiency. Smaller contributions to the uncertainties are caused by uncertainties in initial and final state gluon radiation and uncertainties in the jet energy scale, which affects the efficiency for an event to pass the minimum jet energy requirements.

In summary, we search for the flavor-changing neutral current decays $t \to q\gamma$ and $t \to qZ$ in $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. No statistically significant excess of these events is seen, although one candidate event survives all cuts in each search. Both events have interpretations outside of the FCNC decay hypothesis. In order to set conservative limits, we treat these events as FCNC candidates and set 95% confidence level limits on the branching fractions $B(t \to q\gamma) < 3.2\%$ and $B(t \to qZ) < 33\%$, consistent with Standard Model expectations.

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Generated $t\bar{t}$ Decay	Identified As	Relative Efficiency
$WbWb$	Standard Model	1 (by definition)
$Wb\gamma q$	Standard Model	$0.266 \pm 0.013 \pm 0.005$
$Wb\gamma q$	FCNC	$3.96 \pm 0.17 \mp 0.20$
$WbWb$	FCNC	negligible
$\gamma q\gamma q$	Standard Model	negligible
$\gamma q\gamma q$	FCNC	negligible

TABLE I. Efficiencies and acceptances for $t \rightarrow \gamma q$ decays, normalized to Standard Model top decays. The first uncertainty reflects the uncertainty for all sources except the b quark identification efficiency; the second uncertainty reflects the uncertainty from the b quark identification efficiency.

Generated $t\bar{t}$ Decay	Identified As	Relative Efficiency
$WbWb$	Standard Model	1 (by definition)
$WbZq$	Standard Model	$0.693 \pm 0.035 \mp 0.027$
$WbZq$	FCNC	$0.359 \pm 0.018 \mp 0.044$
$WbWb$	FCNC	$0.022 \pm 0.004 \pm 0.003$
$ZqZq$	Standard Model	$0.062 \pm 0.003 \pm 0.000$
$ZqZq$	FCNC	$0.630 \pm 0.032 \mp 0.077$

TABLE II. Efficiencies and acceptances for $t \rightarrow Zq$ decays, normalized to Standard Model top decays. The first uncertainty reflects the uncertainty for all sources except the b quark identification efficiency; the second uncertainty reflects the uncertainty from the b quark identification efficiency.

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